ELECTRIC ARC WELDER AND METHOD FOR CONTROLLING THE WELDING PROCESS OF THE WELDER

The present invention relates to the field of electric arc welding and more particularly to a novel electric arc welder and a system and method for controlling the welding process performed by the welder.

INCORPORATION BY REFERENCE

The invention relates to an electric arc welder for performing a welding process between an electrode and a workpiece wherein the welding process is comprised of a succession of current waveforms. Such current waveforms are created by a number of individual current pulses occurring at a frequency of at least 18 kHz with a magnitude of each of the current pulses being controlled by a wave shaper or waveform generator. In this type of electric arc welder, the waveform generator or wave shaper digitally controls a digital pulse width modulator, usually a program in the controller DSP. The pulse width modulator controls the switching of a high speed switching type power source, such as an inverter. This waveform control technology implemented in an electric arc welder has been pioneered by The Lincoln Electric Company of Cleveland, Ohio and is generally disclosed in Blankenship 5,278,390. The Blankenship patent is incorporated by reference herein as background illustrating a high speed switching power source, such as a inverter, for controlling a weld process including a series of controlled waveforms determined by the output of a waveform generator or wave shaper.

The invention involves an embedded algorithm for obtaining the root mean square of either the welding current or the welding voltage, as well as average power. The concept of an embedded

system programming of the type used in the present invention is generally disclosed in an article by Jack W. Crinshaw entitled *Embedded Systems Programming* (Integer Square Root) This article published in February 1998 is incorporated by reference herein as illustrating the background technology used in the digital signal programmer of a standard controller associated with an electric arc welder. Also incorporated by reference herein is an article entitled *Electrical Measurements and Heat Input Calculations for GMAW-P Process* dated November 2001.

BACKGROUND OF THE INVENTION

As illustrated in prior patents and literature, electric arc welding has heretofore used the average weld voltage and the average weld current for controlling the operation of the power source in the welder. The digital controller includes a digital signal processor (DSP) for controlling a waveform generator or wave shaper that directs the operation of the normal pulse width modulator. This device creates the waveforms successively used by the welder to perform the welding process. Welders regulate the output current or voltage to an average value such as an average weld current by a feedback loop. For a constant voltage process that is welding in the "spray" region, the average current is an accurate gage of the welding process. However, in pulse welding, the average current and average voltage do not accurately reflect the result of the welding process including the deposition rate, heat zone and penetration. This is explained by a example of an ideal pulse welding process, such as one having 500 amperes for 25% of the time and 100 amperes of background current for 75% of the time has an output current of 200 amperes. However, the average current of the welding process merely indicates the deposition rate and does not reflect the true heat input to the welding operation. Consequently, when the welding process is controlled by a series of repetitive

waveforms, such as A.C. welding or pulse welding, average current values can not control the heat input. Recently, the welding processes have become quite complex and now often involve a number of successive waveforms, such as A.C. current and pulse current, so the old technology of feedback control for the welding process is not completely accurate and requires a substantial amount of on-site manipulation by a person knowledgeable in welding, especially a person knowledgeable in the new waveform welding procedure using a welder, such as shown in Blankenship 5,278,390. With the advent of pulse welding using waveform generators and high speed switching power sources, such as inverters, the obtained weld heat has been adjusted by trial and error. Too much heat causes metal to burn through, especially in thin metal welding. Thus, the welding engineer modulates the average current and average voltage to provide the heat input to the welding process to a level so that burn through is theoretically eliminated. This procedure was applicable, however, only for a pure spray type welding process. This procedure of controlling the heat by the average current and average voltage was not applicable to the new generation of electric arc welders where waveforms are changed to control the welding process. This is the new waveform control technology to which the present invention is directed. The old technology used for non-waveform welding is inapplicable to controlling heat in a controlled waveform type welder. The heat is not known by merely reading the voltage and current when the new waveform type arc welders are employed. Consequently, the welding engineer when using waveform control technology changed the base frequency during pulse welding while maintaining a constant or set average voltage. Using this approach of frequency adjustment of a pulse welding procedure while maintaining a constant voltage, the heat could be adjusted by a trial and error technique. When this trial and error procedure was used to modify the

waveforms in a new waveform welder, the heat could, indeed, be controlled; however, it was not precise and involves substantial technical knowledge combined with the trial and error procedures.

There is a distinct advantage in pulse welding. This welding process lowers the heat into the joint for the same wire feed speed as a "spray" or "globular" weld process. Thus, a lower heat setting can be set at the factory. The welder had a knob to adjust the nominal frequency, for the purpose indicated above. This change in base frequency did adjust the heat at the welding operation. This resulted in a slight change in the power factor of the welding process through the trial and error method when knowing that the average voltage times average current multiplied by the power factor equals the input heat. Thus, by using a knob to change the base frequency, the power factor was changed to determine heat. However, neither the factory nor the welding engineer at the welding site had the capabilities of directly controlling the power factor. Computation of actual power factor on the fly was not realized in prior control systems and method used for electric arc welders even of the type that used a waveform or wave shape control of the welding process. Consequently, with the introduction of the new waveform welding pioneered by The Lincoln Electric Company, there is a need to control the welding parameters to a value that accurately reflects the heat content. Only in this manner can weld parameters be used in a closed loop feedback system, or otherwise, to control the penetration and heat separately in a weld process using generated waveforms.

SUMMARY OF THE INVENTION

With the advent of the new wave shapes developed for electric arc welding, the present invention provides a control of the welding parameters to accurately reflect the heating content

without use of trial and error procedures or the need for on site welding engineers to modulate and control the welding process. The invention is in welding with a series of generated waveforms, such as A.C. welding or A.C. welding.

In order to produce a stable weld while continuously feeding wire into the weld puddle, there are primarily two factors that must be balanced. First, the amount of weld metal wire and its material properties determine how much current is needed to melt the wire. Second, the amount of heat determines the heat affected zone or penetration of the welding process. In the past, an operator dialed in a voltage and wire feed speed and manually adjusted the electric stickout to control the amount of heat put into the weld. Welding literature typically claims that the pulse welding process lowers the current for the same deposition rate of a "spray" procedure. This is technically accurate. The average current is, indeed, much less than the average current of an equivalent "spray" procedure when using "pulse" welding. However, the rms currents of both procedures are about the same. The present invention involves the use of rms current for the feedback loop control of the welding process. Thus, the invention involves the use of rms current and rms voltage for controlling the welding process, especially when using a series of generated pulse waves, such as in A.C. welding and "pulse" welding using the technology described in Blankenship 5,278,390. By using the rms current and rms voltage, a more accurate control of the waveform type welding process is maintained. In accordance with the invention, the rms value and the average value of current and voltage can be used for feedback control. In this aspect of the invention, a first constant is multiplied by the rms value and a second constant is multiplied by the average value of the parameter. These two constants total one, so the constituent of root mean square in the feedback control is adjusted

with respect to the constituent of average in the feedback control. These constants preferably total one. In practice, the rms constant is substantially greater than the average value constant so that normally the rms value is predominate over the average value. It has been found that the rms value more accurately reflects the heating value of the welding process.

In accordance with the invention, the feedback control of the electric arc welder maintains the rms voltage and rms currents constant, while adjusting the calculated real time power factor. This procedure of adjusting the power factor adjusts the heat input to the weld procedure to a desired level.

In the present invention the term "power factor" relates to the power factor of the welding process. This is a parameter obtained by using the present invention through the digital signal processor (DSP) of a welder having an embedded algorithm for calculating the root mean square of both current and voltage. The actual power factor is generated for a closed loop feedback system so that the welding power factor is adjusted to change the average power and, thus, the heat of the welding operation. Consequently, another aspect of the invention is maintaining the rms current constant while adjusting the power factor to change the heat at the welding process. When this is done in a waveform type welder wherein the waveform is created by a number of current pulses occurring at a frequency of at least 18 kHz with a magnitude of each pulse controlled by a wave shaper, the shape of the waveform in the welding process is modified to adjust the power factor. In this aspect of the invention, the current remains constant. This could not be accomplished in other types of welders, nor in waveform control welders, without use of the present invention.

The present invention relates to a control of an electric arc welder of the type wherein a pulse

width modulator, normally in the DSP, controls the current waveform constituting the welding process. By using the present invention, the rms current and rms voltage is obtained for the purpose of combining with the average current and average voltage to produce, not only the average power, but also the actual real time power factor. Consequently, the actual power factor can be adjusted, the actual rms current can be adjusted, or the actual rms voltage can be adjusted. In all of these embodiments, the adjustment of the constructed or calculated parameters modifies the waveform to control the welding process accurately in the areas of penetration and heat input. By having the capabilities of the present invention, power factor manipulation adjusts the heat input of the welding process. In accordance with an aspect of the invention, the feedback of current and voltage is a combination of the rms value and the average value in a method or system where the rms value predominates.

The primary aspect of the present invention is the use of the novel control arrangement in an A.C. pulse welding process using waveform technology involving a wave shaper controlling a pulse width modulator. This type of welding process includes waveform with a positive segment and a negative segment wherein one of the segments has a background current which is lower than the peak current. This pulse is, thus, truncated with a peak current portion normally having a leading edge and trailing edge and a magnitude and a background current with a magnitude and length. A circuit to adjust either the background current or the peak current portion of the pulse is employed to maintain the power factor at a given level. Preferably, the background current magnitude or length is adjusted to maintain the given power factor level. The "given level" is adjusted to change the heat of the welding process. Consequently, the A.C. pulse welding process to which the invention is

particularly applicable utilizes an adjustment of the background current portion to change the power factor and, thus, control the heat of the welding process.

The invention is primarily applicable for use in an electric arc welder of the type having a pulse shaper or waveform generator to control the shape of the waveform in the welding process. This type of welder has a digitized internal program functioning as a pulse width modulator wherein the current waveform is controlled by the waveform generator or wave shaper as a series of current pulses. The duty cycle of these high speed pulses determines the magnitude of the current at any given position in the constructed waveform of the weld process. This type of welder has a high speed switching power source, such as an inverter. The invention involves the combination of this particular type of power source and implementation of the program and algorithm to form the functions set forth above.

In accordance with the invention, there is provided an electric arc welder for performing a given weld process with a selected waveform performed between an electrode and a workpiece. This type of welder generates the waveforms and includes a controller with a digital signal processor. The sensor reads the instantaneous weld current and a circuit converts the instantaneous current into a digital representation of the level of the instantaneous current. The digital processor has a program circuit or other program routine to periodically read and square the digital representation at a given rate. A register in the processor sums a number of squared digital representations to create a summed value. An embedded algorithm in the processor periodically divides the summed value by a number N, which is the number of samples obtained during the sampling process of the waveform. The quotient provided by dividing the summed value by the number of samples is then directed to

the algorithm for taking the square root of the quotient to thereby digitally construct an rms signal representing the root mean square of the weld current. This same procedure is used for obtaining the root mean square or rms signal representing the weld voltage. Consequently, the initial aspect of the invention is the use in a waveform welder, a real time signal indicative of the root mean square of the weld current primarily, but also the weld voltage. These signals have not heretofore been obtainable in an arc welder of the type to which the present invention is directed.

As previously stated, the present invention is directed to an electric arc welder of a specific type wherein a waveform is generated by a waveform generator or wave shaper. Consequently, another aspect of the present invention is the provision of an electric arc welder as defined above wherein the waveform is created by a number of current pulses occurring at a frequency of at least 18 kHz, with a magnitude of each pulse controlled by a wave shaper or waveform generator. The "switching frequency" is the frequency of the pulse width modulator controlling the switching frequency of the power source. This frequency is normally substantially greater than 18 kHz and preferably in the range of 40 kHz.

The invention, as defined above, has a sampling rate for the sensed current and/or voltage. In accordance with another aspect of the present invention, this sampling rate is less than 40 kHz or in another aspect it is in the general range of 5 kHz to 100 kHz. In practice, the sampling rate provides a sample each 0.10 ms. It is anticipated that this rate should have a time as low as 0.025 ms.

In an aspect of the invention, the average power is obtained together with the rms current and the rms voltage. A circuit divides the average power by the rms power to create a signal or level

representing the actual real time power factor of the power source. This power factor is compared with the desired power factor to create a corrective value for the wave shaper whereby the actual real time power factor is held at the desired power factor. This maintains a constant power factor. As explained before, by maintaining a constant power factor with a constant rms current, any tolerances in the welding process are overcome so that the welder will operate identically at the site as it did when set up by the manufacturer. This aspect of the invention is primarily employed for pulse welding and changes the shape of the pulse to obtain the desired constant power factor without changing the root mean square current of the welding process.

In accordance with another aspect of the invention relating to the obtained power factor level, the power factor is adjustable to change the heat of the welding process, especially when using the invention for pulse welding. The waveform generator or wave shaper controls the shape of the waveform to adjust the power factor to maintain it constant or to adjust it for the purposes of controlling heat. When this adjustment is employed, the rms current is maintained constant. Thus, the power factor is adjusted without adjusting or changing the actual current. The rms current determines the melting rate of the metal.

In accordance with another aspect of the present invention there is provided a method of controlling an electric arc welder, of the type defined above, which method comprises calculating the actual power factor of the power source using the rms current and the rms voltage. A desired power factor is then selected for the power source and an error signal is obtained by comparing the actual power factor of the power source to the desired power factor of the power source. This is accomplished by adjusting the waveform by the error signal whereby the actual power factor is held

at the desired power factor.

The primary object of the present invention is the provision of an electric arc welder for performing A.C. pulse welding using a waveform generator or wave shaper, whereby the heat of the process is controlled by changing the background current of either the negative or positive pulse of the waveform.

In accordance with another object of the present invention is provision of a welder, as defined above which welder adjusts the peak portion of one pulse in the A.C. pulse welding method to control the desired heat or power factor of the welding process.

Yet another object of the present invention is the provision of an electric arc welder, as defined above, which welder utilizes an A.C. pulse welding waveform and adjusts the power factor to control the heat of the welding operation.

These and other objects and advantages will become apparent from the following description.

BRIEF DESCRIPTION OF DRAWINGS

The invention is apparent from the drawings which are:

FIGURE 1 is a block diagram illustrating an electric arc welder utilizing the present invention for controlling the waveform generator;

FIGURE 2 is a flow chart and block diagram illustrating the computer program of the digital signal processor utilized for performing the preferred embodiment of the present invention;

FIGURE 2A is a cycle chart of digital signal processor utilized for performing the preferred

embodiment of the present invention as set forth in FIGURE 2 showing the timing function of the digital signal processor;

FIGURE 3 is a flow chart of the program for implementing aspects of the cycles in FIGURE 2A after creation of an event signal T;

FIGURE 3A is a waveform graph for the logic applied to the state table in FIGURE 3;

FIGURE 4 is a current waveform graph illustrating the sampling concept used in the present invention to create current signals used in obtaining rms values;

FIGURE 5 is a block diagram and flow chart of the cycle counter in a field programmable gate array incorporated in the controller and a block diagram of the use of this cycle counter information in the digital signal processor (DSP) to obtain an event signal T;

FIGURE 5A is a graph of the pulse current and logic at one terminal of the flow chart shown in FIGURE 5 when pulse welding is used instead of A.C. welding;

FIGURE 6 is a flow chart of the preferred embodiment of the present invention as performed in the digital signal processor during the cycles show in FIGURE 2A;

FIGURE 7 is a block diagram of the program used to create the rms current signal using the present invention;

FIGURE 8 is a block diagram like FIGURE 7 for creating the rms voltage signal;

FIGURE 9 is a block diagram showing the aspect of the invention for creating an average power signal;

FIGURE 10 is a block diagram showing the aspect of the present invention for creating the actual power factor of the welding process for use in the present invention;

FIGURE 11 is a block diagram of a welder utilizing the power factor value of FIGURE 10 to maintain a constant power factor for the weld process in pulse welding;

FIGURE 12 is a block diagram, as shown in FIGURE 11, wherein the power factor value from FIGURE 10 is adjusted manually to control the power factor of the welding process while maintaining the rms current constant;

FIGURE 13 is a block diagram showing a standard digital filter controlled by the relationship of the actual power factor to the set power factor to adjust the shape of the weld current by adjusting the waveform generator input to maintain a constant power factor;

FIGURE 14 is a block diagram showing control of the welder by a relationship of average voltage and a rms voltage compared with a set voltage signal to adjust the shape of the waveform to maintain a set voltage;

FIGURE 15 is a block diagram showing control of the welder by a relationship of average current and a rms current compared with a set current signal to adjust the shape of the waveform to maintain a set current;

FIGURE 15A is a current graph showing how the waveform is adjusted to maintain the set value, be it current, voltage or power factor;

FIGURE 16 is a block diagram showing a digital filter to adjust the wire feed speed based upon a comparison of a set voltage to a signal involving a component of average and rms voltage and also a digital filter to adjust the waveform upon a comparison of a set current to a signal involving a component of average and rms current;

FIGURE 17 is a block diagram similar to the block diagram illustrated in FIGURE 12

wherein the power factor value of FIGURE 10 is adjusted manually to control the power factor of the welding process, while maintaining the rms current constant to thereby adjust the heat by modifying the shape of the waveform controlled by the wave shaper;

FIGURE 18 is a diagram illustrating the waveform of the welding process to which the invention is particularly directed, including a peak current portion and a background current portion in an A.C. pulse welding mode;

FIGURE 19 is a diagram similar to FIGURE 18 showing how the shape of the waveform is adjusted to maintain a desired welding heat by using the present invention;

FIGURES 20 and 21 are block diagrams showing the circuit for adjusting the background current of the waveform to control peaks using the generated real time power factor value; and,

FIGURES 22 and 23 are diagrams similar to FIGURES 20, 21 for adjusting the peak current of the waveform used to generate the welding operation to control heat by using the real time power factor value.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference to FIGURE 1, electric arc welder **10** is shown in block diagram form. A three-phase rectifier **12** provides power to high speed switching-type power supply **14** across a DC link in the form of input leads **16, 18**. In a preferred embodiment, high speed switching-type power supply **14** is an inverter, such as a Power Wave welding power supply available from Lincoln Electric Company of Cleveland, Ohio. However, a high speed switching chopper or other high speed switching-type power supply can also be employed. High speed switching-type power supply **14**

performs a preselected welding process. In accordance with present welding technology, high speed switching-type power supply **14** preferably switches at about 18 kHz or higher, and more preferably at 40 kHz or higher. High speed switching-type power supply **14** energizes welding circuit **20** that includes inductor **22** and electrode **24** forming an arc gap with workpiece **26** during performance of the welding operation. Typically, electrode **24** is a forward advancing welding wire from a supply spool. The welding wire is driven toward workpiece **26** at a selected wire speed during performance of the welding operation.

Controller **30** controls high speed switching-type power supply **14** during the welding operation. In accordance with the present welding technology, controller **30** is a digital device including waveform generator **32** that outputs power level waveform **34** represented by a line that is the input to pulse width modulator **36**. Pulse width modulator **36** produces pulse train **38** (represented by a line) of pulses with pulse widths corresponding to the power level of waveform **34**. In other words, waveform **34** is converted into pulse width modulated pulse train signal **38** by pulse width modulator **36**. Pulse width modulator **36** produces pulses of controlled width at a frequency preferably above 18 kHz, and more preferably about 40 kHz or higher, which is the input to high speed switching-type power supply **14**. The power supply switching is controlled by pulse-width modulated pulse train **38** to energize welding circuit **20** in accordance with power level waveform **34**.

Waveform **34** implements a desired welding process. Typically, a welding process is made up of a waveform train of repeating waveforms. For pulse welding, power level waveform **34** has a preselected wave shape for generating a welding process pulse. The average power or true heat

produced in the welding process implemented by waveform **34** over a time interval $[T_1, T_2]$ is given by:

$$P_{avg} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} v(t) \cdot i(t)\, dt \qquad (1),$$

where P_{avg} is the average power, v(t) is the instantaneous voltage, i(t) is the instantaneous welding current, $v(t) \cdot i(t)$ is the instantaneous power, and T_1 and T_2 are the starting and ending time points of the time interval, respectively, of the integration. In the case of a substantially periodic waveform, the average power can be expressed in terms of root-mean-square (rms) voltage and rms current according to:

$$P_{avg} = V_{rms} \cdot I_{rms} \cdot PF \qquad (2),$$

where the rms voltage, V_{rms}, and rms current, I_{rms}, are given by:

$$V_{rms} = \sqrt{\frac{\int_{T_1}^{T_2} [v(t)]^2\, dt}{T_2 - T_1}} \quad , \quad I_{rms} = \sqrt{\frac{\int_{T_1}^{T_2} [i(t)]^2}{T_2 - T_1}} \qquad (3),$$

respectively, and PF is the power factor. In computing the average power and the rms current and voltage values for waveform **34** that implements pulse welding, the time interval $[T_1, T_2]$ preferably

corresponds to one pulse or a plurality of pulses. In waveform-controlled welding, the pulse time interval may vary for successive pulses. Hence, in the described preferred embodiment, the starting and stopping times T_1 and T_2 are extracted from waveform **34** as event signals T determined from a characteristic feature of waveform **34**.

Equation (3) can be rewritten to define the power factor PF according to:

$$PF = \frac{P_{avg}}{V_{rms} \cdot I_{rms}} \quad (4).$$

There is in general a close relationship for substantially any waveform **34** between the rms voltage and current values and the average power.

In contrast, the average voltage, V_{avg}, and average current, I_{avg}, given by:

$$V_{avg} = \frac{\int_{T_1}^{T_2} v(t)\,dt}{T_2 - T_1} \ , \ I_{avg} = \frac{\int_{T_1}^{T_2} i(t)\,dt}{T_2 - T_1} \quad (5),$$

have a close relationship with the average power only for certain waveforms, such as are used in constant-voltage "spray" type welding. However, if, for example, the waveform includes a stepped pulse that is 500 amperes for 25% of the time and 100 amperes for 75% of the time, the rms value is 265 amperes, while the average value is 200 amperes. In this case, the rms values provide a more accurate true heat value.

With continuing reference to FIGURE 1, controller **30** of electric arc welder **10** implements an exemplary pulse welding process in which the magnitude of waveform **34** is controlled using an

rms current **40** that is calculated from an instantaneous welding current I_a **42** measured across shunt **44**. In the constant current welding process shown in FIGURE 1, rms current **40** is compared with set rms current **46** by digital error amplifier **48** to produce error signal **50** that controls an amplitude of waveform **34** to maintain a constant rms current. Similarly, for a constant voltage welding process, control is suitably based on an rms voltage calculated from instantaneous welding voltage V_a **52** measured across the weld by voltmeter **54**.

With reference to FIGURE 2, computation of the rms current from instantaneous welding current I_a **42** includes processing with analog-to-digital converter **56** to produce digitized instantaneous current **58**, which is the input to digital signal processing block **60**. Digital signal processing block **60** performs the current squared integration of Equation (3) digitally as a Riemann sum, dividing the current into time intervals Δt defined by oscillator **62** for the summing. The digitizing interval Δt for the Riemann sum is suitably about 0.1 milliseconds to provide adequate samples for each pulse or repetition of waveform **34**. Sample-and-hold circuit **64** holds the digitized current for the period Δt, and squaring processor **66** computes the square of the held current value.

In order to enable continuous summation of rms current in parallel with related processing such as the computation of the square-root operation of Equation (3), the summing preferably employs two alternating storage buffers, namely first buffer **70** (identified as Buffer A), and second buffer **72** (identified as Buffer B). Values are stored in the active buffer at intervals **76, 78** that are preferably in a range of about 0.025-0.100 milliseconds. When first buffer **70** is active, switch **80** transfers values at time intervals Δt to first buffer **70**, which accumulates the current-squared values and also maintains a sample count N of a number of accumulated current samples. As a background

process during accumulation in first buffer **70**, the contents of second buffer **72** are processed by division processor **82** to divide by the number of samples N, and by square-root processor **84** to complete computation of the root-mean-square calculation of Equation (3).

At a selected event signal T generated by a characteristic of waveform **34**, the operation of buffers **70**, **72** switches. Second accumulator **72** is cleared, and switch **80** subsequently transfers current-squared samples into second accumulator **72**. As a background process during accumulation in second buffer **72**, the contents of first buffer **70** are processed by division processor **86** to divide by the number of samples N, and by square-root processor **88** to complete computation of the root-mean-square calculation of Equation (3).

FIGURE 7 shows a simplified block diagram of digital signal processing block **60**, which omits the details of the alternating summation buffers **70**, **72** and related switching circuitry that are shown in detail in FIGURE 2. In FIGURE 7, current-squaring block **66**, switch **80**, and alternating summation blocks **70**, **72** are represented by a single summation block **100** that sums current-squared samples between occurrences of the event signal T triggered by a characteristic of waveform **34**, and also maintains the count N of the number of accumulated samples. Division background processes **82**, **86** of FIGURE 2 are represented by a single normalization background process **102** in FIGURE 7. Square-root background processes **84**, **88** of FIGURE 2 are represented by a single square root background process **104** in FIGURE 7.

With reference to FIGURE 8, it will be appreciated that digital signal processing block **60** shown in FIGURE 2 and represented in simplified form in FIGURE 7 is readily adapted to perform rms voltage calculations, by replacing measured instantaneous current I_a **42** with instantaneous

voltage V_a **52** measured by voltmeter **54** of FIGURE 1. FIGURE 8 shows rms voltage digital signal processing block **60'** in a simplified form analogous to the simplified form of FIGURE 7. The digitized voltage is processed by sample-and-hold circuit **64'** which holds the digitized voltage for the period Δt. Voltage-squared summation block **100'** sums voltage-squared samples and maintains a count N of the number of accumulated voltage samples. Preferably, summation block **100'** uses alternating summation buffers analogous to buffers **70, 72** shown for the current-squared summation in FIGURE 2. Normalization background process **102'** divides the voltage-squared sample sum by the number of samples N. Square root background process **104'** takes the square root to complete implementation of the rms voltage V_{rms} mathematically shown in Equation (3).

With reference to FIGURE 9, it will be appreciated that digital signal processing block **60** shown in FIGURE 2 and represented in simplified form in FIGURE 7 is similarly readily adapted to perform average power calculations, by inputting both measured instantaneous current I_a **42** and measured instantaneous voltage V_a **52**. FIGURE 9 shows average power digital signal processing block **60''** in a simplified form analogous to the simplified form of FIGURE 7. Sample-and-hold circuits **64, 64'** which hold the digitized current and voltage, respectively, for the period Δt, are accessed by current-times-voltage summation block **100''** which sums current-times-voltage samples and maintains a count N of the number of accumulated current-times-voltage samples. Preferably, summation block **100''** uses alternating summation buffers analogous to buffers **70, 72** shown for the current-squared summation in FIGURE 2. Normalization background process **102''** divides the current-times-voltage sample sum by the number of samples N to produce the average power P_{avg} shown mathematically in Equation (1).

Digital signal processing blocks **60, 60', 60''** compute the rms current, the rms voltage, and the average power as Riemann sums. FIGURE 4 shows exemplary current waveform **120** that is digitally sampled. Each digital sample is represented by a rectangular sample bar **122** of time duration Δt and height corresponding to the digitized value of current waveform **120** held by sample-and-hold circuit **64** at the time interval Δt.

Digital signal processing blocks **60, 60', 60''** are optionally implemented as separate processing pathways that execute in parallel. However, in a preferred embodiment digital signal processing blocks **60, 60', 60''** use some common digital signal processing blocks into which the sampled voltage and current signals are time-domain multiplexed. Such a multiplexing approach reduces the amount of circuitry required. Each summation (voltage-squared, current-squared, and voltage-times-current) has its own alternating summation buffer set (for example, summation buffer set **70, 72** for summing current-squared values as shown in FIGURE 2).

With reference to FIGURE 2A, a suitable process cycling for the time-domain multiplexing is shown. The process cycling employs four cycles **130, 132, 134, 136** each occupying one-fourth of the sampling period Δt. For the exemplary Δt equal 0.1 millisecond, each of the four cycles **130, 132, 134, 136** occupies 0.025 milliseconds. During first cycle **130**, the voltage V_a and current I_a are digitized and sample/held. During second cycle **132**, the current-squared is computed and added to the current-squared summation. During third cycle **134**, the voltage-squared is computed and added to the voltage-squared summation. During fourth cycle **136**, a check is performed to determine whether an event signal T has been detected, and the sample count is incremented. Moreover, throughout the cycling other processing, such as computation of the square roots of values stored in

the inactive summation buffers, can be performed as background processes. Similarly, digital signal processing welding control operations, such as waveform shaping described by Blankenship 5,278,390, can be performed as background control processes during the cycling.

With reference to FIGURES 2 and 2A, and with further reference to FIGURE 3A and FIGURE 6, the cycling as applied to the current-squared calculation is described. FIGURE 3A illustrates current waveform **34** extending between first event signal T_1 and second event signal T_2. Event signals T_1, T_2 are are suitably generated by a circuit controlled by waveform **34**. In FIGURE 3A, the circuit generates event signal T_1 responsive to onset of the rising edge of current pulse **140**, and the circuit generates event signal T_2 responsive to onset of the rising edge of current pulse **142**. Thus, there is a current pulse between each two successive event signals T. Rather than detecting the rising edge, the event signals can instead be generated by detecting another characteristic of the pulse, such as the falling edge of the current pulse.

During the time interval between event signal T_1 and event signal T_2, current-squared samples are accumulated in summation buffer **70**, as indicated in FIGURE 3A by the notation "Adding to Buffer A". Each occurrence of second cycle **132** of FIGURE 2A adds another current-squared sample to buffer **70**. Although not shown in FIGURES 2, 3A, or 6, voltage-squared samples and average power samples are preferably being accumulated in their respective buffers during the other cycles of the four-cycle process of FIGURE 2A. Detection of event signal T_2 is indicated by detection block **150** of FIGURE 6. Responsive to detection **150**, buffers **70, 72** are switched so that buffer **72** is used to accumulate current-squared samples of next pulse **142** of waveform **34,** while buffer **70** in which the current-squared samples of pulse **140** are accumulated is shifted **152** into the

background. In background processing, the current-squared sum is divided **154** by the number of samples N and the square-root is taken **156** to complete the rms algorithm. The computed rms current value for pulse **140** is written **158** to a register for use in welding process control.

With reference to FIGURE 5, a suitable method for generating event signals T is described. A field programmable gate array (FPGA) includes cycle counter state machine **170** that updates two-bit counter **172**. State machine **170** is configured to increment two-bit counter **172** each time the state changes. Each change of state corresponds to an occurrence of event signal T. In the digital signal processing (DSP), two-bit comparator **174** compares the value of two-bit counter **172** with previous counter value register **176** during fourth cycle **136** of FIGURE 2A. A change in the value of two-bit counter **172** indicated by the comparison corresponds to an occurrence of event signal T. Responsive to event signal T, digital gate **178** loads the new value of two-bit counter **172** into previous counter value register **176**. In this arrangement, the value stored in two-bit counter **172** is not significant; rather, a change in the counter value is detected.

With continuing reference to FIGURE 5 and with further reference to FIGURE 5A, the polarity of waveform **34** along with an auxiliary "Misc2" signal are input to state machine **170** through"OR" gate **174**. This arrangement enables the FPGA to generate event signals T for pulse welding and for a.c. welding. In the case of a.c. welding, Misc2 is set to zero so that the polarity signal feeds through to cycle counter state machine **170**. For pulse welding, Misc2 is set to one when the arc is shorted, and zero when the arc is not shorted. FIGURE 5A shows a graph of pulse current **180** and the value of Misc2 **182** when pulse welding is used instead of A.C. welding.

With continuing reference to FIGURE 5 and with further reference to FIGURE 3, events

initiated by an occurrence of event signal T are described. At fourth cycle **136** of FIGURE 2A, the digital signal processing performs a check **190** to see if an occurrence of event signal T has been detected. This is done by comparing the current value of two-bit counter **172** with stored counter value **176** using two-bit comparator **174**. If no change in counter value has occurred, the digital signal processing continues to loop through the four states **130, 132, 134, 136** of FIGURE 2A. However, if check **190** detects an occurrence of event signal T, the rms value is computed **192** as set forth in Equation (3) and in accordance with FIGURES 2 and 7. Computation **192** is a background digital signal process. Additionally, a buffer switch **194** is performed so that whichever buffer (buffer A **70** or buffer B **72**) had been active is switched to the background, and whichever buffer (buffer B **72** or buffer A **70**) had been the background buffer is made the active accumulation buffer.

Exemplary digital signal processing circuitry and associated FPGA circuitry for substantially real-time computation of rms voltage V_{rms}, rms current I_{rms}, and average power P_{avg} have been described with reference to FIGURES 1-9. The described digital signal processing circuitry implements Equations (1) and (3) using Riemann sums, and is exemplary only. Those skilled in the art can readily modify the illustrated digital circuitry or substitute other digital circuitry to perform these computations or substantial equivalents thereof. The illustrated circuitry provides certain features that may be optionally omitted or modified. For example, separate and independent digital signal processing pathways can be provided for computing each of the rms voltage V_{rms}, rms current I_{rms}, and average power P_{avg} values. In this arrangement, time-domain multiplexing aspects of the circuitry can be omitted. Rather than having two alternating accumulators, a single accumulator can be employed in conjunction with a storage register that stores the previous sum for background

normalization/square root processing. Moreover, if the digital signal processing is sufficiently fast or if parallel processing is employed, the temporary storage may be omitted entirely, and the normalization/square root processing performed substantially in real time for intervals between successive event signals T. Still further, a trapezoidal or otherwise-shaped integral element can be substituted for rectangular sample bars **122** of the Riemann sum illustrated in FIGURE 4. Those skilled in the art can make other modifications to the exemplary digital signal processing and FPGA circuitry illustrated herein for implementing Equations (1) and (3) as digital circuitry.

With reference to FIGURE 10, digital signal processing block **200** computes the power factor (PF) in accordance with Equation (4) from the rms voltage V_{rms}, rms current I_{rms}, and average power P_{avg} values. The denominator of Equation (4) is computed using multiplier **202** acting on the rms current I_{rms} and rms voltage V_{rms} output by digital signal processing blocks **60, 60'** of FIGURES 7 and 8, respectively. The average power P_{avg} output by digital signal processing bloc **60"** of FIGURE 9 is divided by this denominator using division block **204** to compute the power factor PF.

With continuing reference to FIGURE 10 and with further reference to FIGURE 11, electric arc welder **10** of FIGURE 1 is readily adapted to implement a constant power factor control of the weld process in pulse welding. Controller **30'** is a modified version of controller **30** of FIGURE 1. Digital error amplifier **48'** produces error signal **50'** based on the power factor PF. Digital error amplifier **48'** compares the power factor PF output by digital signal processing block **200** (shown in detail in FIGURE 10) with PF set value **46'**. Waveform generator **32'** modifies selected waveform shape **210** based on error signal **50'** as described in Blankenship 5,278,390 which is incorporated by reference herein.

With continuing reference to FIGURE 10 and with further reference to FIGURE 12, electric arc welder **10** of FIGURE 1 is similarly readily adapted to implement a constant current welding process in which heat input to the weld is controlled by adjusting the power factor PF. Controller **30''** is a modified version of controller **30** of FIGURE 1. The rms current **40** is compared with set rms current **46** by digital error amplifier **48** to produce current error signal **50** as in FIGURE 1. Additionally, a second digital error amplifier **220** produces power factor error signal **222** by comparing the power factor PF output by digital signal processing block **200** (shown in detail in FIGURE 10) with adjustable welding heat set value **224**. Waveform generator **32''** modifies selected waveform shape **210** based on error signals **50**, **222** as described in Blankenship 5,278,390.

With reference returning to FIGURE 11 and with further reference to FIGURE 13, in digital error amplifier **48'** the power factor error signal optionally incorporates digital filtering. As shown in FIGURE 13, digital error amplifier **48'** includes difference operator **232** that computes difference signal **234** which is proportional to a difference between the computed power factor and power factor set value **46'**. Difference value **234** is input into digital filter **236** which generates control signal **50'** for adjusting the waveform shape in accordance with the method described in Blankenship 5,278,390. In one suitable embodiment, digital filter **236** is an infinite impulse response filter. The digital filter can be used to amplify the signal, smooth the signal, remove high frequency signal components, or otherwise adjust the control signal.

With reference to FIGURE 14, a digital error amplifier **240** for constant voltage control is shown. Digital error amplifier **240** includes difference operator **242** that computes difference signal E(n) **246** given by:

$$E(n) = V_{set} - (a \cdot V_{avg} + b \cdot V_{rms}) \quad (6),$$

where V_{set} is a set voltage value, V_{avg} is an average voltage value computed in accordance with Equation (5), a is an average voltage weighting factor implemented by multiplier **250**, V_{rms} is the rms voltage of Equation (3) that is output by digital signal processing block **60'** of FIGURE 8, and b is an rms voltage weighting factor implemented by multiplier **252**. It will be recognized that difference signal E(n) **246** can be biased by adjusting the weighting factors a and b toward average voltage control, rms voltage control, or a selected weighted combination of average voltage and rms voltage control. Because the rms voltage is typically a better measure of the true heat input to the weld by the welding process, the rms weight b is preferably greater than the average weight a, that is, b>a. Moreover, the sum of the weighting factors is preferably unity, that is, a+b=1. Optionally, difference signal E(n) **246** is processed by digital filter **254**, such as an infinite impulse response filter, to amplify, smooth, or otherwise manipulate difference signal E(n) **246** to produce control signal **256** for adjusting the waveform shape in accordance with the method described in Blankenship 5,278,390.

With reference to FIGURE 15, a digital error amplifier **260** for constant current control is shown. Digital error amplifier **260** includes difference operator **262** that computes difference signal E(n) **266** given by:

$$E(n) = I_{set} - (a \cdot I_{avg} + b \cdot I_{rms}) \quad (7),$$

where I_{set} is a set current value, I_{avg} is an average current value computed in accordance with Equation (5), a is an average current weighting factor implemented by multiplier **270**, I_{rms} is the rms current

of Equation (3) that is output by digital signal processing block **60** of FIGURE 7, and b is an rms current weighting factor implemented by multiplier **272**. It will be recognized that difference signal E(n) **266** can be biased by adjusting the weighting factors a and b toward average current control, rms current control, or a selected weighted combination of average current and rms current control. Because the rms current is typically a better measure of the true heat input to the weld by the welding process, the rms weight b is preferably greater than the average weight a, that is, $b>a$. Moreover, the sum of the weighting factors is preferably unity, that is, $a+b=1$. Optionally, difference signal E(n) **266** is processed by digital filter **274**, such as an infinite impulse response filter, to amplify, smooth, or otherwise manipulate difference signal E(n) **266** to produce control signal **276** for adjusting the waveform shape in accordance with the method described in Blankenship 5,278,390.

With reference to FIGURE 15A, an exemplary waveform shape adjustment in accordance with the waveform shape adjustment method of Blankenship 5,278,390 is illustrated. Two waveforms **280**, **282** are shown in solid and dashed lines, respectively. For $b=1$ and $a=0$ in Equation (6) or Equation (7) (for voltage control or current control, respectively), waveforms **280, 282** have equal rms values. However, the average value is generally different for waveforms **280**, **282**.Compared with waveform **280**, waveform **282** has a reduced voltage or current background magnitude and an increased voltage or current magnitude in the pulse.

Moreover, it will be appreciated that the pulse repetition period of waveforms **280, 282** may be different. This difference in repetition period is accounted for in the digital signal processing by performing the Riemann sums of Equations (1), (3), and (5) over intervals between successive event signals T, instead of performing the Riemann summing over time intervals of fixed length.

Generating event signals T at a rising pulse edge or other identifiable characteristic of the waveform allows the summation interval to track the repetition period of the waveform as the repetition period is adjusted by the waveform shaping.

With reference to FIGURE 16, two digital error amplifiers **300, 302** compute current and voltage error signals for use in a constant current, constant voltage welding process control. Digital error amplifier **300** includes difference operator **310**, weighting factors a **312** and b **314**, and digital filter **316**. Digital error amplifier **300** has the same voltage inputs and general circuit topology as amplifier **240** of FIGURE 14; however, digital error amplifier **300** produces control signal **318** for controlling wire feed speed during the welding process. With increasing output of amplifier **300** the wire feed speed should be decreased, while with decreasing output of amplifier **300** the wire feed speed should be increased. Digital amplifier **302** includes difference operator **330**, weighting factors c **332** and d **334**, and digital filter **336**. Digital error amplifier **302** has the same current inputs and general circuit topology as amplifier **260** of FIGURE 15, and produces control output **338** for adjusting the waveform shape in accordance with the method described in Blankenship 5,278,390. Hence, the waveform shape and the wire feed speed are simultaneously controlled using digital error amplifiers **300, 302** to keep both voltage and current constant.

FIGURES 17-23 disclose the use of the present invention for an A.C. pulse welding operation, wherein the heat of the A.C. pulse welding operation is controlled by changing certain aspects of waveform **400**, best show in FIGURES 18, 19. Referring now to FIGURE 17, Power Wave power source **14** produces a waveform across electrode **24** and workpiece **26** through choke **22**. A voltage in line **5L** is created across the arc to provide a real time representation of the arc

voltage. In a like manner, shunt **44** produces a voltage in line **42** which is the instantaneous arc current. As previously described, waveform generator **32** has an output represented by lead **34** to control the duty cycle of the pulse width modulator **36.** The modulator is normally preformed by software and has a pulse rate established by oscillator **36a**. Of course, a hardwired pulse width modulator is sometimes employed. The digital or analog voltage on line **38** determines the wave shape of the welding operation waveform performed by the power source. A Power Wave sold by The Lincoln Electric Company of Cleveland, Ohio is the illustrated, preferred power source. This unit is disclosed generally in Blankenship 5,278,390. The waveform created by generator **32** has a shape controlled by wave shaper **210** so the output voltage, digital or analog, on line **210a** determines the signal in line **34** that generates the specific current waveform at the welding operation. As so far described, the technology is explained above and is well known in the art. In accordance with of the invention, digital comparator **220,** having an output **222** compares the real time power factor signal represented by the value in line **220a** with the desired heat to be created as represented by the digital or analog voltage at line **224**. Thus, output voltage in line **222** is the voltage indicating the relationship between the real time power factor and the desired heat, which is represented as the desired power factor in line **224**. In accordance with the invention, an adjusting circuit **220b** provides a signal in line **222a** that is responsible to the different signal in line **222.** Thus, as the signal in line **222** varies, the output voltage in line **222a** modifies the wave shape in wave shaper **210** to change the shape of the waveform. This action obtains the desired heat as referenced by the manually adjusted voltage in line **224**. The block diagrams shown in FIGURE 17 are performed digitally by controller software using standard DPS to perform waveform technology

control of the electric arc welder. The voltage on line **222a** modifies the A.C. pulse waveform structured by wave shaper **210** to maintain the desired heat based upon a relationship with the real time power factor. To accomplish this objective, various aspects of waveform **400** are adjusted by circuit **220b**.

To illustrate various portions of the waveform which are adjusted to control heat, waveform **400** is shown schematically in FIGURES 18 and 19. Waveform **400** comprises one of a succession of A.C. pulses including a positive pulse segment **402** and a negative pulse segment **404**. In the preferred embodiment, positive pulse segment **402** is constructed with a peak current portion **410** and a background portion **412** with peak level 430. The magnitude of the peak current is represented as level **418**. As shown in FIGURE 19, heat adjustment of waveform **400** is accomplished by changing peak level **418**, shown as dashed lines **402a** and represented by **c**. Adjustment of the magnitude of the peak current is one implementation of the invention, where the shape of the waveform is modified to control heat, based upon the real time power factor of the welder. Height **414** of background current portion **412** is indicated as adjustable by dashed lines **414a**. In a like manner, leading edge **416** is adjustable to change the heat of the welding operation as indicated by dashed line **416a**. Magnitude change **a** of the background current and the change **b** in the width of background current are the primary adjustments implemented to cause waveform **400** to create the desired welding heat, while maintaining I_{rms} constant. The primary aspect of the invention for modifying peak current portion **410** is adjustment of peak current magnitude as indicated by **c** as the distance between line **402a and line** 402. However, peak portion **410** normally has a leading ramp **420** and a trailing ramp **422** as shown in the second occurrence of waveform **400**. These two ramps

are adjustable to change the heat at the welding operation under the control of the real time power factor. As illustrated in FIGURE 19, the dimensions **a, b**, and **c** as well as the angles of the ramps indicated by **d**, are adjustable to control heat. Circuits to accomplish these adjustments are illustrated in FIGURES 20-23. In these figures, digital circuit **220b** controls the wave shaper **210** by the voltage in line **222a**. FIGURE 20 illustrates the use of circuit **220b** to adjust dimension **a**. The power factor value in line 220a (preferably digital) is obtained by dividing the average power in line 204a by the product in line 204e obtained by multiplying I_{rms} in line 204b by V_{rms} in line 204c with circuit 204d. Dimension **b** is adjusted by the circuit shown in FIGURE 21. Using the circuits shown in FIGURES 20 and 21 the magnitude of the background current in portion **412** is varied so that the power factor signal at line **220a** is compared with the desired heat represented as a voltage on line **224** to change the background current. Thus, the background current is adjusted to maintain the desired heat caused by the waveform **400**. The circuits in FIGURES 22 and 23 implement adjustments of the dimensions **c, d**. This changes the magnitude of the peak current or the angle of one or both ramps **220, 222**. In this manner, the peak current portion of waveform **400** is adjusted to create the desired heat. Other aspects of the waveform are adjustable to control the desired heat based upon the real time power factor of the welding operation using a circuit as shown in FIGURES 20-23.

The invention has been described with reference to certain preferred embodiments illustrated in FIGURES 17-23. Modifications in these embodiments can be made without departing from the intended spirit and scope of the present invention as defined in the appended claims.